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Ice core evidence for climate change in the Tropics: implications for our future

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Abstract

Reliable meteorological observations for climate reconstruction are limited or absent prior to A.D. 1850 for much of the Earth and particularly in both tropical South America and the Tibetan Plateau region of central Asia. Over 50% of the Earth's surface lies between 30°N and 30°S and 75% of the world's inhabitants live and conduct their activities in these tropical regions. Thus, much of the climatic activity of significance to humanity, such as variations in the occurrence and intensity of the El Niño-Southern Oscillation and monsoons, are largely confined to lower latitudes. Moreover, the variability of these tropical systems and particularly that of the tropical hydrological system in response to regional and global climate forcing are not well understood. Fortunately, ice core records are also available from selected high altitude, low and mid-latitude ice caps. The ice core studies described here were undertaken as part of a long-term program to acquire the global-scale, high-resolution climatic and environmental history essential for understanding more fully the linkages between the low and the high latitudes. Two ice core records, one covering the last full glacial cycle from the Guliya Ice Cap, China (35°N; 6200 m asl) and one from Huascarán, Peru, which reveal significant cooling during the Last Glacial Cycle Maximum (LGM $\sim$ 20,000 yr BP) are compared with preliminary data coming from the new Sajama, Bolivia (18° S, 6550 m asl) and the Dasuopu, Himalaya (China, 28°N, 7200 m asl) cores. Lower $\delta^{18}O$ values (equivalent to cooling of $\sim$ 8°C) contribute to the growing body of evidence that the tropical climate was cooler and more variable during the last glacial cycle and has renewed current interest in the tropical water vapor cycle. The new tropical ice core records raise additional questions about our understanding of the role of the tropics in global climate. Unfortunately, as a result of recent warming, all known tropical glaciers and ice caps are retreating and soon will no longer continue to preserve viable paleoclimatic records. The characteristics of the current warming will be examined and compared to earlier periods of climatic warming such as the transition form the last glacial into the current interglacial as well as other periods within the Holocene. It is important to distinguish natural variation in the climate system from the anthropogenic influences superimposed during the last century. These tropical ice cores offer long-term perspectives of accumulation, temperature, atmospheric dust and "greenhouse" gas concentrations against which recent variations may be assessed, with particular relevance for lower latitude regions where most people live.

1. Introduction

The significance of recent climatic and environmental variations must be evaluated from a perspective provided by longer-term proxy climate records. Such histories may be reconstructed from ice cores recovered from carefully selected, high-elevation tropical ice caps, as well as from polar ice sheets. Ice caps and ice sheets continuously record the chemical and physical nature of the Earth's atmosphere. Ice cores drilled from carefully selected sites often provide paleoenvironmental records with seasonal, annual, decadal and centennial resolutions. Such cores, some of which extend through the last major glaciation (over 100,000 yr ago), have been recovered from both polar and lower latitudes. Over the last two decades high-quality ice core records have been obtained from six low-latitude, high-altitude sites (Thompson et al., 1985, 1986, 1989, 1995, 1997, 1998). Of these six sites, three records from the Qinghai-Tibetan Plateau and two from the tropical Andes of South America extend back at least into the Late Glacial Stage (LGS). Each of these sites, which differ both in their glaciological and meteorological environments, contain records of local, regional and large-scale climate variations. Data from the upper sections of these cores have been integrated with other proxy indicators to yield a high-resolution global perspective of the Earth's climate over the last 1000 yr. Together, these records provide a historical reconstruction of most of the world's major climate zones. They

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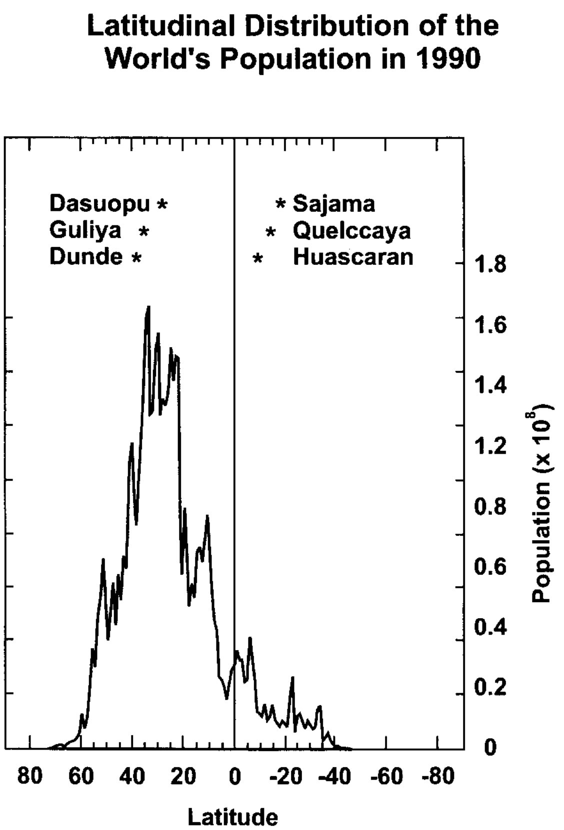


Fig. 1. Location of low latitude–high altitude drill sites relative to the 1990 human population on the Earth.

demonstrate considerable natural variability during the present climate epoch, including a number of climate extremes such as the so-called "Little Ice Age". Some of the variations appear to be regional in extent, while others are clearly global or near-global.

Records recovered from low-latitude ice caps are of particular interest as they are located in areas where climatic changes may directly and significantly affect human activities. Today, more than 75% of the world's population lives in areas directly impacted by variations in tropical climate, which underscores the importance of long-term climate and environmental records from the area. Fig. 1 illustrates the latitudinal distribution of the world's population in 1990 (after Yi-Fan Li, 1997 Database 1016), along with the relative positions of the low latitude ice cores sites. Recent research suggests that tropical proxy records may be more representative of global mean annual temperatures than proxy records from higher latitudes (Bradley, 1996). This paper examines the evidence of climate change over annual to millennial time scales from the Dunde, Guliya and Dasuopu sites in the low-latitude Northern Hemisphere with records from Quelccaya, Huascarán and Sajama located in the tropical Andes in the Southern Hemisphere. These records will be shown as recorders of El Niño-Southern Oscillation and monsoon intensities. The mounting evidence for recent, strong warming in the tropics is examined, which is a signaled by the rapid retreat and even disappearance of ice caps and glaciers at high elevation, and the implications of the changes for our future are discussed.

Fig. 2 shows a general schematic depicting the processes as snow is deposited and metamorphosed into ice. The relative importance of each phase will change from site to site and is very much dependent on the amount of annual snowfall, mean annual and seasonal temperature range at the depositional site. Although details have been addressed in the literature (Fisher et al., 1985; Paterson, 1994; Grootes, 1995), these processes have not been studied extensively in the low latitudes. While drilling these low latitude–high altitude sites, at least two ice cores were recovered in order to demonstrate the reproducibility of the records and to yield insight into the variability which might exist within the each ice cap.

The quality of the preservation and reproducibility of the records is illustrated in Fig. 3 using the oxygen isotopic ($\delta^{18}O$) record from Huascarán, Peru, which at 9°S is the lowest latitude ice core record recovered. Among the measured ice core parameters, $\delta^{18}O$ is one of the most susceptible to post-depositional changes because of the presence of melt-water and/or changes in temperature during densification. In 1980, during the original reconnaissance expedition to Huascarán, a 10 m firn core was drilled and analyzed at the Ohio State University (Thompson et al., 1984). Fig. 3 shows a comparison between the $\delta^{18}O$ records from this short core recovered in 1980 and a long core drilled to bedrock in 1993 (Thompson et al., 1995) on an ice equivalent depth scale. Other than some minor accumulation variations and some slight signal attenuation, the records are very compatible, with an isotopic mean difference of only 0.23‰ between 1980 and 1993. It is interesting to note that the amount of ice thinning that has occurred over this 13-yr period is roughly 22% (5.56–4.32 m). This agrees well with an average thinning value of 23% for Huascarán Core 2 (drilled in 1993) which was derived using the long-term time/depth relationship based on layer counting and artificially "burying" 5.56 m of surface ice by 13 yr of accumulation using a two-parameter thinning model.

The other issue of importance is the spatial variability of signal across the col of Huascarán. Of the two cores drilled to bedrock in 1993, Core 1 (160.4 m) was sectioned in the field into 2677 samples ranging from 13 cm at the top to 3 cm at the base, which were then melted and poured into 2 or 4 oz bottles, and sealed with wax. Core 2 (166.1 m), drilled approximately 100 m from the Core 1 site, was returned frozen to the laboratory at OSU in 1 m sections and subsequently was cut into 4675 samples. In Fig. 4 the $\delta^{18}O$ profiles from these two cores are plotted on the same graph, illustrating the good reproducibility of the records for the upper (A.D. 1934 to 1993)

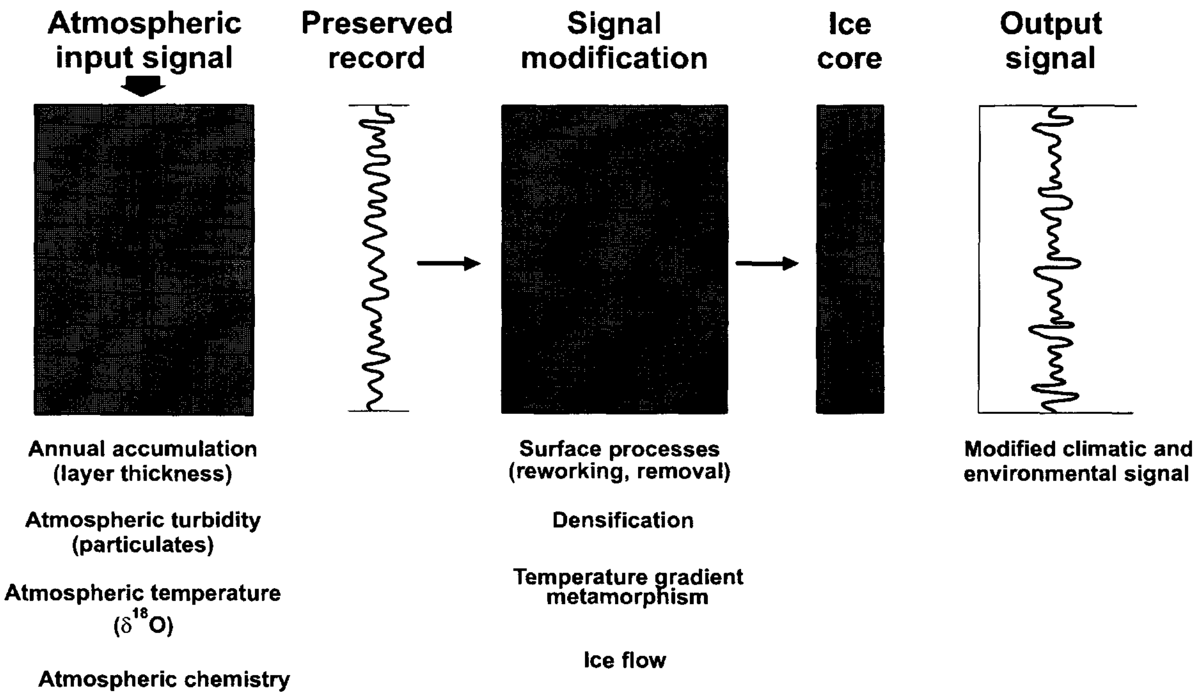


Fig. 2. Schematic indicating how atmospheric climate and environmental signal can be modified through surface processes such as drifting and removal of snow by wind, the densification process as snow becomes ice and as temperature gradients change from day to night and summer to winter and ice flow can thin the annual layers after deposition. These processes lead to a modified climatic and environmental signal being preserved in the glacier archives.

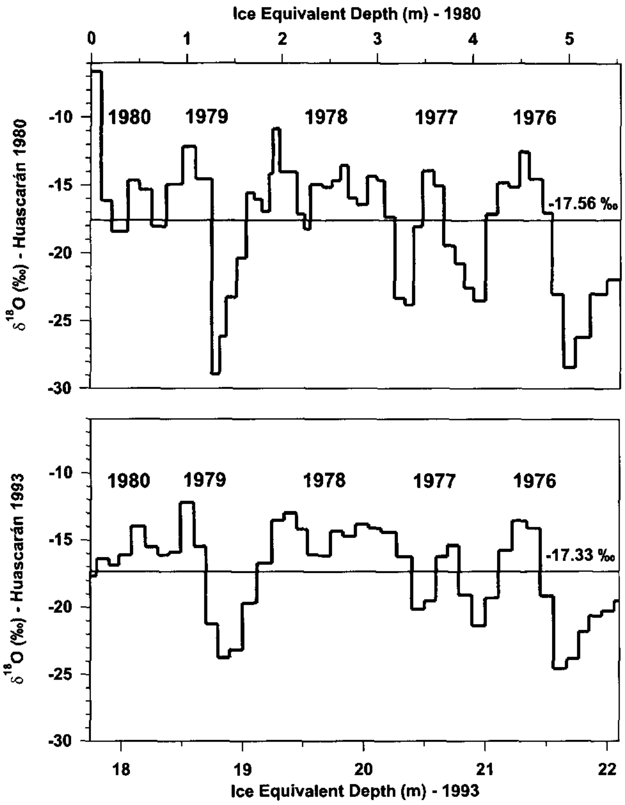


Fig. 3. Comparison of isotopic records recovered from 10 m core drilled in 1980 from col of Huascarán with the same period 13 yr later as measured in the 1993 Huascarán core 2. Comparison of these records demonstrates that very little alteration of the input signal occurred with time and depth.

sections of these cores where resolution is highest. By means of signal reproduction experiments like this, plus calibration programs which are being performed for some of these archives (e.g. China; Yao et al., 1996, Huascarán; Davis et al., 1995 and Sajama; Hardy et al., 1998; Vuille et al., 1998), we are beginning to understand the causes of signal variations which are observed in modern ice core records. However, the atmospheric input signal or the signal modification processes going on today may not necessarily be representative throughout the Holocene, or under completely different regimes, such as those during the Late Glacial Stage.

In the tropical cores, the annual δ^{18}O oscillations show an inverse relationship with temperature, unlike the seasonal variations in the high latitudes (Thompson and Dansgaard, 1975; Grootes et al., 1989; Rozanski et al., 1997). In the tropical profiles, the most depleted values occur during the warm (wet) season because on the annual time scale, temperature and precipitation compete as controlling agents on isotopic composition in tropical snowfall. However, the decadal-to century variability remains positively correlated with temperature. This longer-term correlation is confirmed by the presence of both major and minor large-scale climate events, such as the Little Ice Age on Quelccaya (Thompson et al., 1986), the early Holocene Optimum in Huascarán (Thompson et al., 1995) and the Younger Dryas and the Last Glacial Stage in Sajama (Thompson et al., 1998).

The waxing and waning of major continental ice sheets during glacial and interglacial stages is recorded in ice

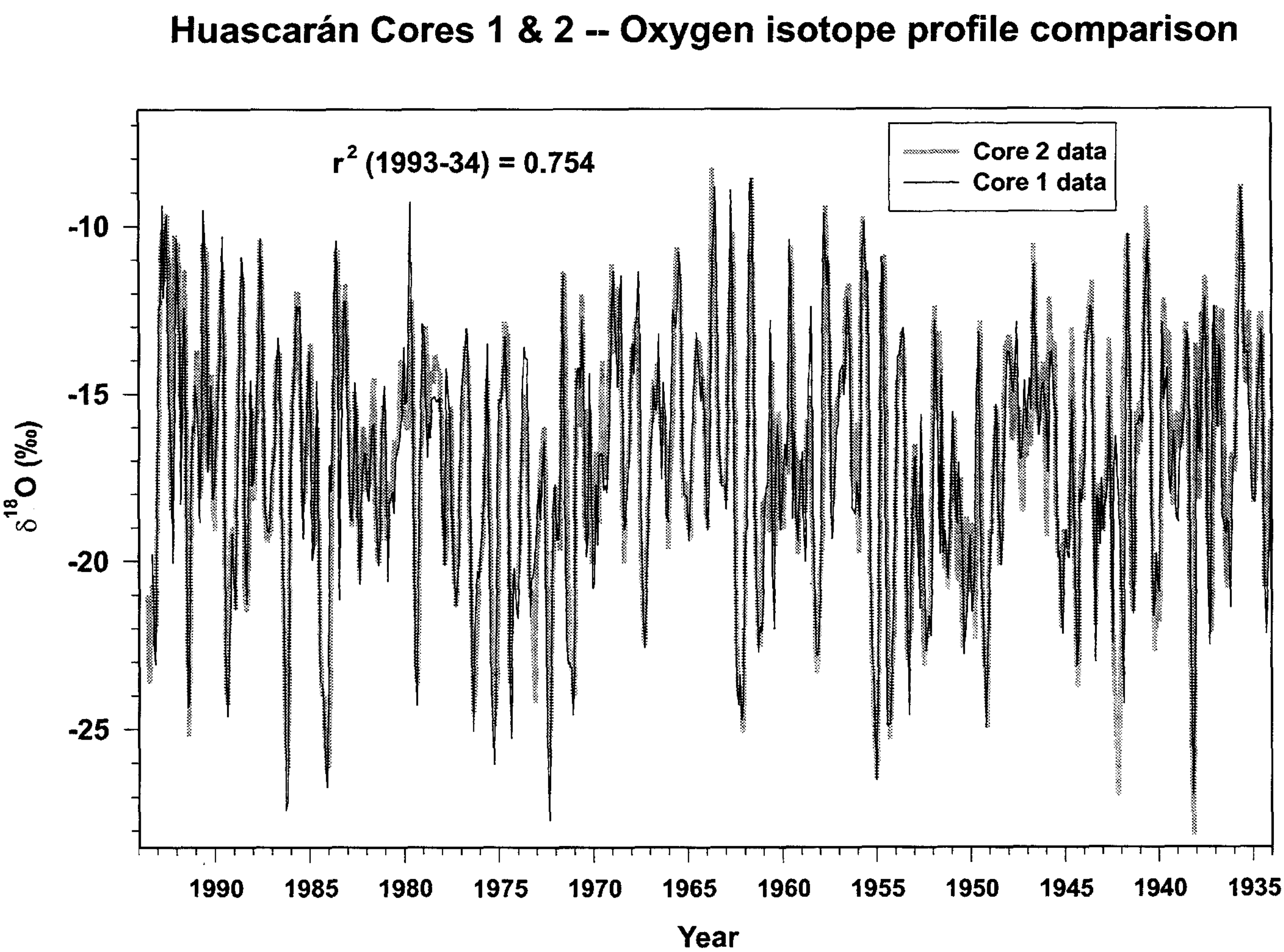


Fig. 4. Profiles of $\delta^{18}O$ plotted in time are compared between two cores drilled on the col of Huascarán. The sites are separated by a 100 m horizonal distance, but show little impact of snow drifting or other factors on the reproducibility of the record from site to site.

cores from both polar and lower latitude regions. However, the shorter term and less drastic climate variations during the Holocene apparently were not globally synchronous; in fact, they may appear prominently in some records but be wholly absent from others. Indeed, the climate histories from various sites in the polar regions display different trends. For example, from about A.D.1500 to 1880, a period of more negative $\delta^{18}O$ values is prominent in a number of sites in East Antarctica but absent in a number of West Antarctic sites (Thompson et al., 1993). $\delta^{18}O$ has been established as a proxy for atmospheric temperature in polar latitudes (Craig, 1961; Dansgaard et al., 1973) such that more negative values are indicative of colder conditions. On the other hand, an out-of-phase relationship in temperature relationship is observed over the long term between the ice core records of East and West Antarctica, and is also present in the instrumental temperature records of this century (Mosley-Thompson et al., 1991). The $\delta^{18}O$ history from the Antarctic Peninsula, however, reveals a strong, persistent warming trend since the 1930s that is absent in East Antarctica and the Greenland Ice Sheet. In fact, with the exception of the Antarctic Peninsula, there is little evidence for recent warming in the polar ice cores.

In contrast to the abundance of records from the polar regions, ice core histories from the mid-latitudes to the tropics are more limited. The recently recovered ice core climate records and results from glaciological investigations on the Tibetan Plateau and in the tropical Andes of South America strongly and consistently indicate a 20th-century warming (Thompson et al., 1989, 1993).

The ice core records from the Qinghai-Tibetan Plateau contribute to the Austral-Asian transect of an international project under the Past Global Changes (PAGES) Pole-Equator-Pole (PEP II) program. Those from sites located in the tropical Andes of South America contribute to the PAGES Pole-Equator-Pole (PEP I) Program. In the next section, the similarity of the tropical records is discussed relative to short-term interannual variability, as well as millennial-scale Holocene versus LGS conditions. They are then compared to selected ice core records and parameters from the polar regions. The abruptness, timing, and magnitude of select climate events over the last 25,000 y is discussed in light of possible forcing mechanisms. The significance of large magnitude abrupt events increases significantly when they can be demonstrated to exist not only in the high latitude polar regions but also in the tropics.

2. The records from the Tibetan Plateau

Annual variations in snow-cover on the high Qinghai-Tibetan Plateau may be important because of the effect of surface albedo on the strength of the Asian monsoon (Sirocko et al., 1993). Barnett et al. (1989) suggested that the monsoon intensity may be affected by the extent and duration of Eurasian snow cover. More extensive snow cover, or snow lasting later in the summer season, tends to utilize the available sensible heat to melt the snow and evaporate soil moisture, thus diminishing the energy to warm the Plateau surface. This may result in a less intense summer low-pressure system and reduced monsoon intensity. On longer time scales, model simulations indicate that increases in snow and ice cover during the Last Glacial Maximum (LGM) on the Tibetan Plateau, along with the resulting increases in albedo, may have caused weakening of the monsoonal circulation (Kutzbach et al., 1998).

The histories of climatic and environmental variation have been reconstructed from three sites on the Plateau (Fig. 5). In 1987 two cores recovered from the Dunde Ice Cap (38°N, 96°E, 5325 m asl) in the Qilian Mountains on the northeastern margin of the Qinghai-Tibetan Plateau provided detailed records of Holocene and (LGS) climate in the sub-tropics (Thompson et al., 1989). Chemical and microparticle analyses of the cores showed that the lower sections, which encompassed the LGS, were characterized by more negative $\delta^{18}O$, a 2.5-fold increase in dust concentration and decreased soluble aerosol concentrations in comparison with the upper 127 m. These results indicate that LGS conditions in this region were apparently colder, wetter and dustier than during the Holocene. The changes in ice chemistry and dust concentrations marked an abrupt transition from glacial conditions which occurred rapidly around 10,000 yr BP. Pollen preserved in the ice cores provides a sensitive record of Holocene climatic changes and vegetational response in the northern Plateau at time scales ranging from millennia to centuries and decades (Liu et al., 1998). High pollen concentrations between 10,000 and 4800 yr BP suggest that the summer monsoon probably extended beyond its present limit to reach Dunde and western Tibet in response to orbital forcing. The $\delta^{18}O$ profiles of the Dunde cores is presented in Fig. 6, and show that the most recent 50 yr (1938–1987) was the warmest period in

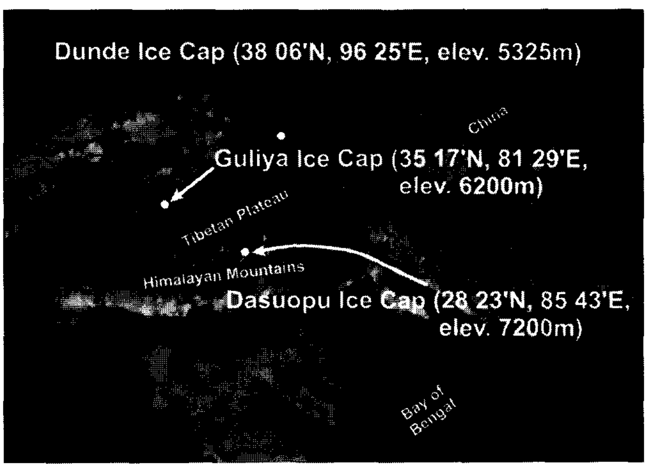


Fig. 5. Location and elevation of the Dunde, Guliya and Dasuopu ice core sites on the Tibetan Plateau.

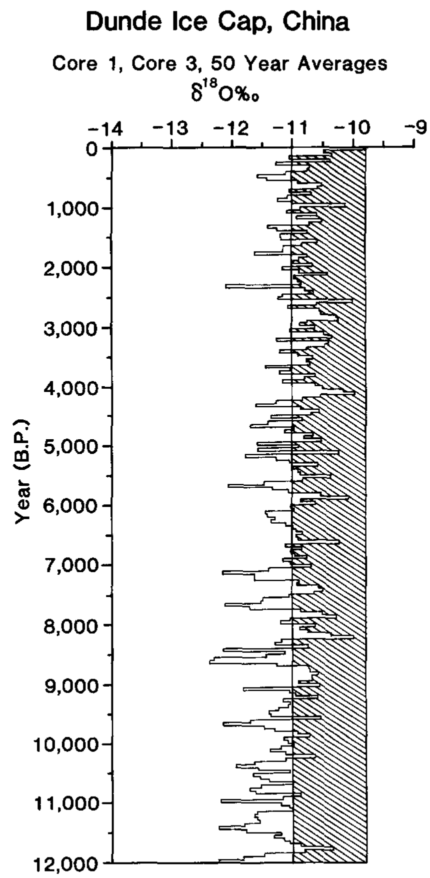


Fig. 6. Fifty-year averages of $\delta^{18}O$ for the last 12,000 y from Cores 1 and 3 on the Dunde ice cap, China. The reference line at $-11‰$ represents the long-term average of the records; projections into the shaded area indicate warmer-than-average periods. Note that the most recent 50-yr period (1937–1987) is the warmest since the end of the last glacial stage.

the last 12 millennia for the northeastern section of the Tibetan Plateau.

On a longer time scale, an ice-core record from the Guliya ice cap (35°N, 81°E; 6200 m asl) on the western side of the Plateau provides evidence of regional climatic conditions over the entire last glacial cycle (Thompson et al., 1997). In fact, ^{36}Cl analysis suggests that the deepest 20 m of this 308.6 m core may be more than 500,000 yr old. The $\delta^{18}O$ change for the most recent deglaciation is $\sim 5.4‰$, which is much greater than the 2‰ transitional change in the Dunde record. Three interstadials which correspond to marine stages 3, 5a and 5c are characterized in the Guliya record by increased $\delta^{18}O$ values, as are the Holocene and the Eemian ($\sim$ 124,000 yr ago). The magnitude of the $\delta^{18}O$ profile variations in the Guliya ice core demonstrate a pattern similar to the magnitude of the CH_4 profile variations from the polar ice cores, indicating that the global CH_4 levels and the tropical hydrological cycle are linked.

Although the Dunde and Guliya ice caps provide valuable long-term paleoclimate histories, the fact that they are located in regions of low accumulation means that they contain limited annual resolution. However, the Dasuopu Glacier (28°N, 85°E, 7200 m asl), which is located on the south central rim of the Plateau, lies in a region of very high annual monsoonal precipitation. Dasuopu is located in a region directly affected by the Asian monsoon system, which influences the most heavily populated region in the world and is recognized as a significant component of the global atmospheric circulation. In 1997, three deep ice cores were recovered from this site and will provide records which will fill a gap in the regional paleoclimate records. Core 1 (159.6 m) was retrieved from a site at 7020 m asl on Dasuopu Glacier, and Cores 2 (149.2 m) and 3 (167.6 m) were drilled to bedrock on the summit of the col (7200 m asl). The temperature at the ice/bedrock contact is $-13.8°C$, indicating that this is the coldest non-polar glacier ever

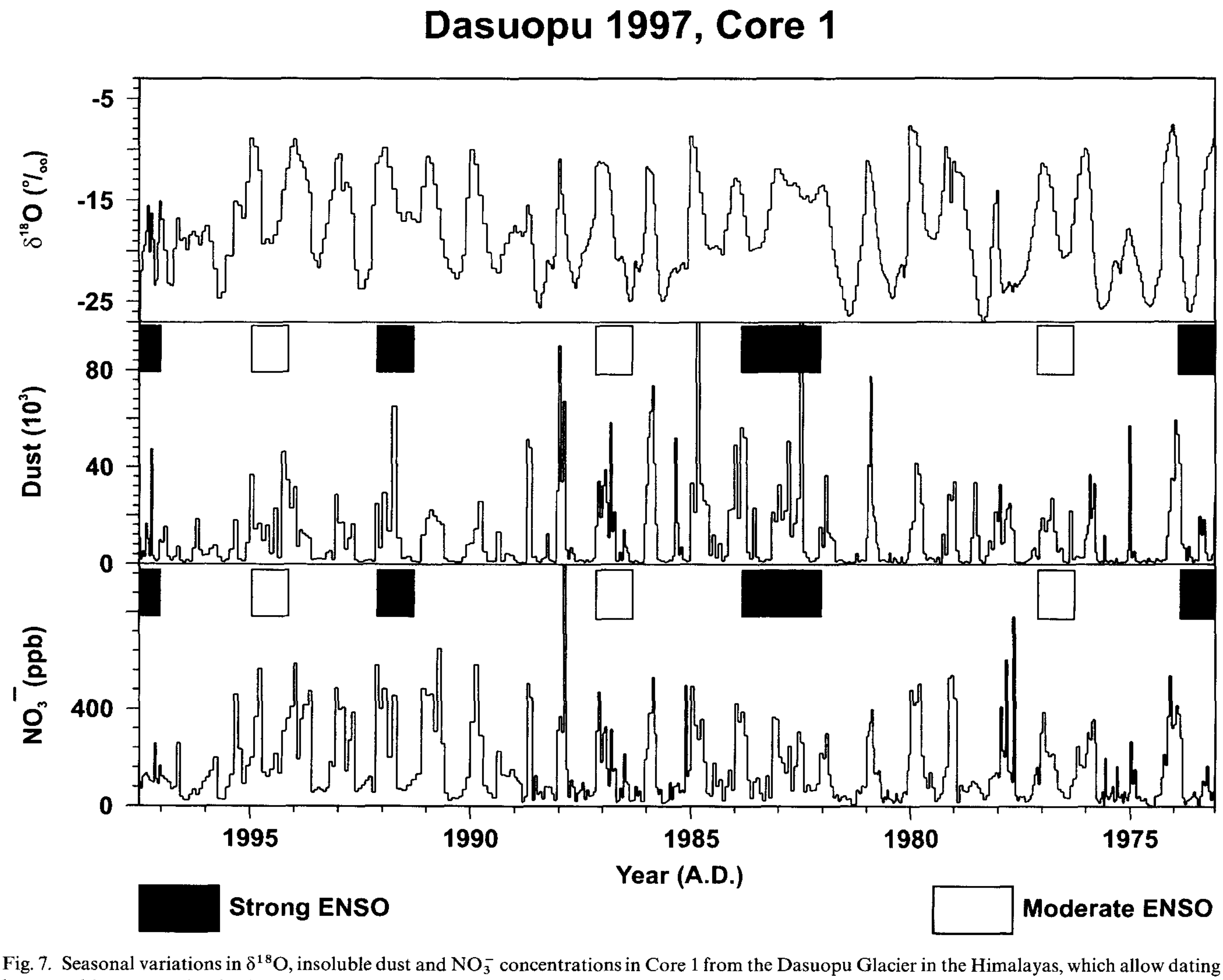


Fig. 7. Seasonal variations in $\delta^{18}O$, insoluble dust and NO_3^- concentrations in Core 1 from the Dasuopu Glacier in the Himalayas, which allow dating by annual layer counting in the upper 150 m of the core.

drilled. The fact that the ice is frozen at the bed suggests that Cores 2 and 3 contain long records. Indeed, preliminary surveys of dust concentrations and $\delta^{18}O$ suggest that the two deep cores contain glacial stage ice.

Analyses of $\delta^{18}O$, dust, Cl^-, NO_3, SO_4^{2-}, Ca^{2+}, Na^+, NH^{4+}, K^+, and Mg^{2+} in the upper part of Core 1 indicate that the upper section of this glacier has the best preserved annual layers of any site in the low latitudes from which ice cores have been recovered. Fig. 7 illustrates the period from 1973 to 1997 from the Core 1 site and shows the well-defined annual signal recorded in $\delta^{18}O$, insoluble dust and nitrates, while a 60-m profile shown in Fig. 8 extends the record of oxygen isotopes and insoluble dust through the firn/ice transition at 45 m. These data demonstrate that the post depositional processes have a minimal impact on the Dasuopu archive. The average measured accumulation of snow is 2.11 m for the period from August 1996 to September, 1997 and is consistent with the annual layer determination made using seasonal variations in $\delta^{18}O$, dust and chemistry in the cores (Figs. 7 and 8).

The high resolution of these records, coupled with those recovered from the Andes of South America, will allow examination of the decadal to centennial-scale teleconnections which exist between the opposite sites of the Pacific Ocean basin, as well as the interannual relationships between the Asian monsoon and the El Niño-Southern Oscillation (ENSO). Observations of the short time series shown in Figs. 7 and 8 suggest that ENSO years (such as 1982 and 1991) may have a very enriched (less negative) $\delta^{18}O$ signal at the top of the Himalayas. This may be due to reduced snowfall during the warm phase of the ENSO event, leading to less deposition of the more depleted monsoon precipitation. The distinct annual resolution preserved in these cores may allow the investigation of the long term relationship of the variability of the monsoons and the relationship with ENSO over the last 1000 to 2000 yr.

Fig. 9 illustrates a comparison between the net annual accumulation and $\delta^{18}O$ records from Dasuopu Core 1 with precipitation and temperature records (for the period 1956–1993) from the nearest meteorological station located in Xigaze, a town on the Plateau about 320 km east of Dasuopu at an elevation of 3836 m asl, 3180 m lower than the ice core drill site. Both the annual net accumulation measured in the Dausopu ice cores and the annual Xigaze precipitation measurements show deceasing trends toward the present (Fig. 9a), while mean

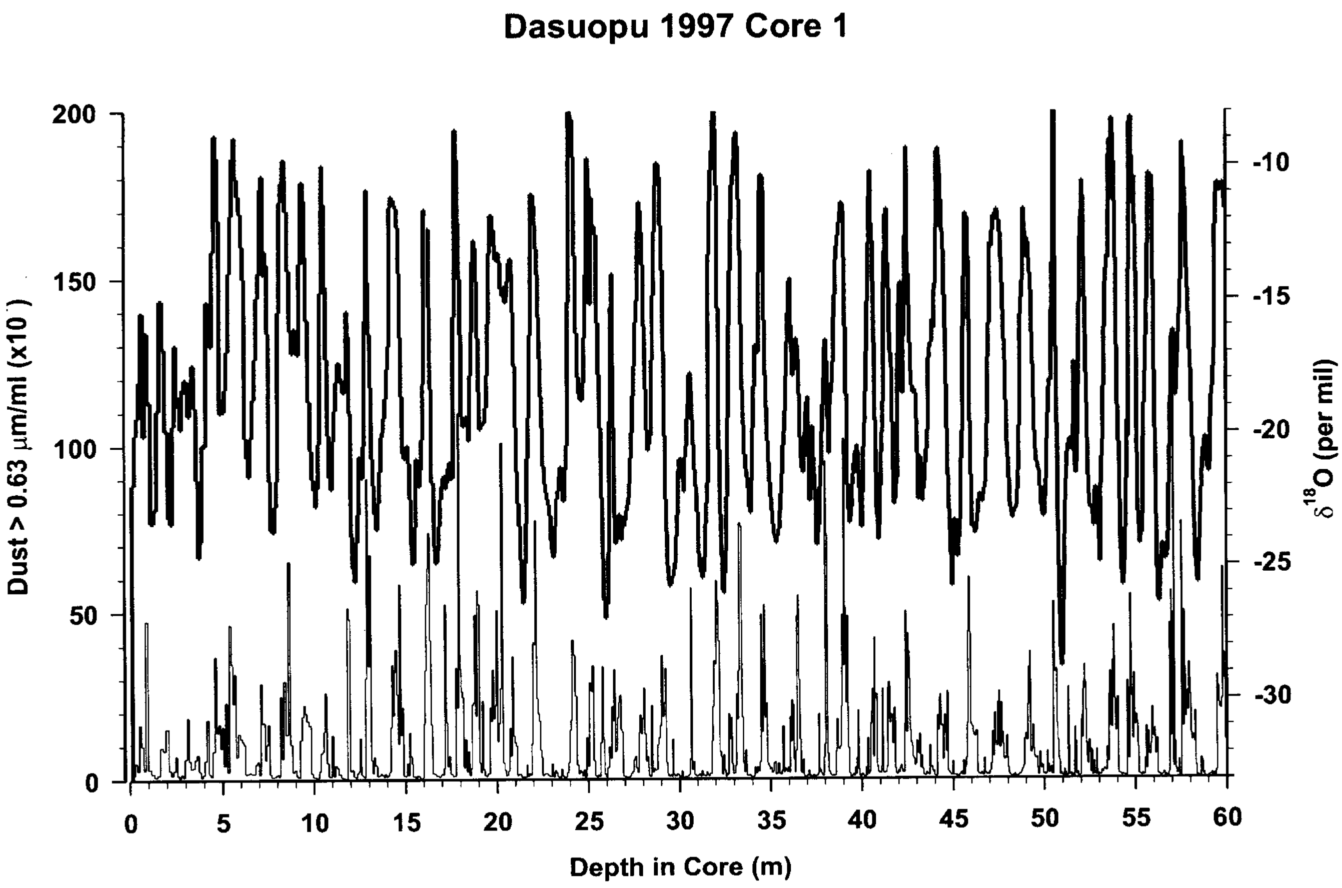


Fig. 8. The upper 60 m of Dasuopu Core 1 shows the very large 15 + ‰ seasonal range in $\delta^{18}O$ and the very distinct seasonal dust variations produced by the strong southwest monsoon influence on the site.

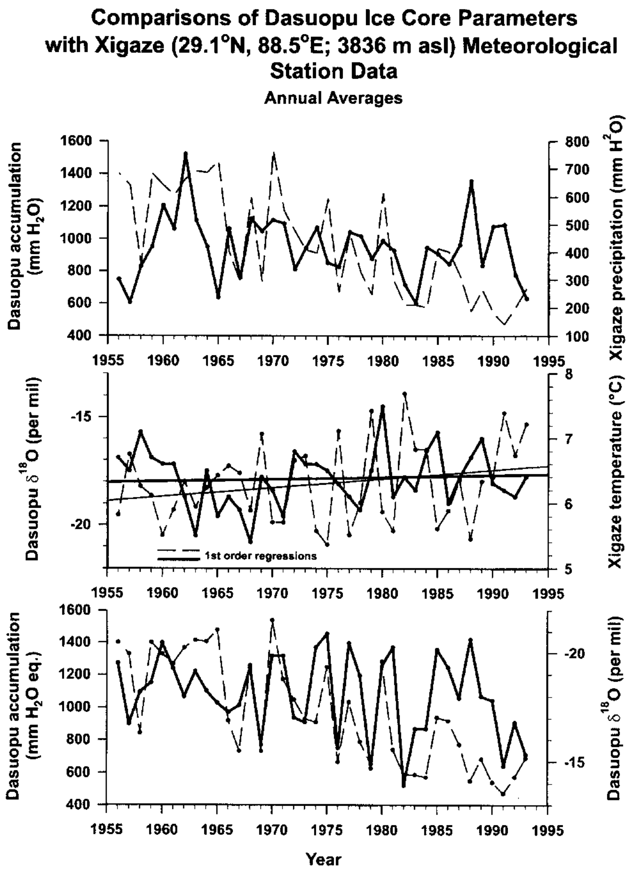


Fig. 9. Comparisons of the mean annual Dasuopu ice core parameters of $\delta^{18}O$ and net balance with the Xigaze meteorological station data of temperature and precipitation. The station is located on the Tibetan Plateau, 320 km to the east of the Dasuopu drill site and at a site which is 3184 m lower in elevation than the ice core drill site.

annual $\delta^{18}O$ increases with mean annual Xigaze temperature over the same period (Fig. 9b). Fig. 9c demonstrates a correlation between the isotopic composition of monsoonal precipitation and the amount of annual accumulation measured in Core 1, where high net balance years are associated with depleted annual mean $\delta^{18}O$.

3. The records from the tropical Andes of South America

This section presents an overview of three ice core sites in the tropical Andes of South America (Fig. 10). The first long-term tropical ice core records ever recovered came from the Quelccaya ice cap in the southern Andes of Peru (Thompson et al., 1984, 1985, 1986, 1988). Two cores from the summit (5670 m asl) provided a 1500 yr history of climate and general environmental conditions including droughts, volcanic activity, moisture sources, temperature, and glacier net balance. Annual variations in visible dust layers, dust concentrations, $\delta^{18}O$, conductivity, plus calibration by the identification of an ash layer

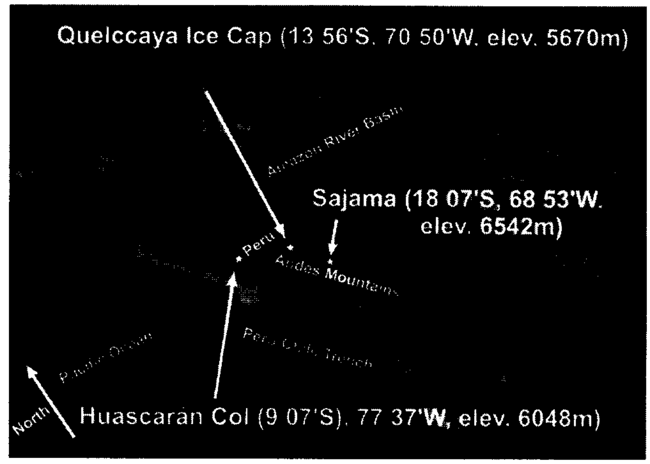


Fig. 10. Map showing the locations and elevations of the three tropical ice cores sites in the Andes of South America.

from the documented eruption of Huaynaputina (A.D. 1600), permitted accurate dating and time-scale verification. The fact that the so-called 'Little Ice Age', or LIA (1520 to 1880 A.D.) stands out as significant climatic event in the $\delta^{18}O$ and electrical conductivity profiles confirms the large-scale character of this event (Thompson et al., 1986).

More recently, ice cores recovered from Huascarán and Sajama have provided tropical records covering the past 25 millennia. Two cores from the col of Huascarán in the north-central Andes of Peru contain a paleoclimatic history extending well into the LGS (Thompson et al., 1995) and include evidence of the Younger Dryas (YD) cool phase (Fig. 11). Glacial stage conditions at high elevations in the tropics appear to have been as much as 8–12°C cooler than today, the atmosphere contained 200 times as much dust, and the Amazon Basin forest cover may have been much less extensive as seen as reduction in nitrate concentrations in Fig. 11. The 8‰ increase in $\delta^{18}O$ from the LGS to the Holocene is comparable to that in polar ice core records. These data imply that the tropical Atlantic was possibly 5 to 6°C cooler during the LGS than the present. Between 11,000 and 9000 yr BP, the $\delta^{18}O$ profile indicates that the temperature increased to a record high, then decreased gradually, culminating with the LIA (200 to 500 yr before present). A strong warming has dominated the last two centuries. One of the most striking features of the Holocene record is the large dust event centered on 4.5 kyr BP. This dust event is believed to represent a 300 yr major drought event which could be concurrent with larger scale event which disrupted climate and culture through out the world (e.g. Kerr, 1998)

The climate of the tropical Andes is marked by annual dry seasons (May–October) which are identifiable in all the ice core records as elevated values of $\delta^{18}O$, dust and anion concentrations, especially nitrate (NO_3^-). Each

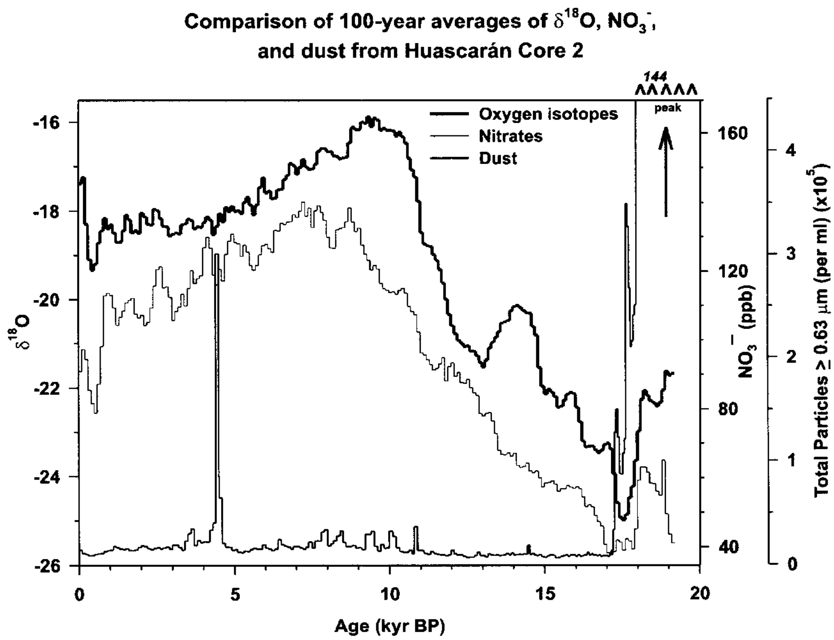


Fig. 11. Comparison of the 100-yr averages of $\delta^{18}O$, NO_3^-, and large particles from Huascarán over the last 20,000 yr. The time-scale has been fine tuned from that presented in the initial publication (Thompson et al., 1995) and is based on a combination of ice flow model, matching of $\delta^{18}O$ (Bard et al., 1987), $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ measurements.

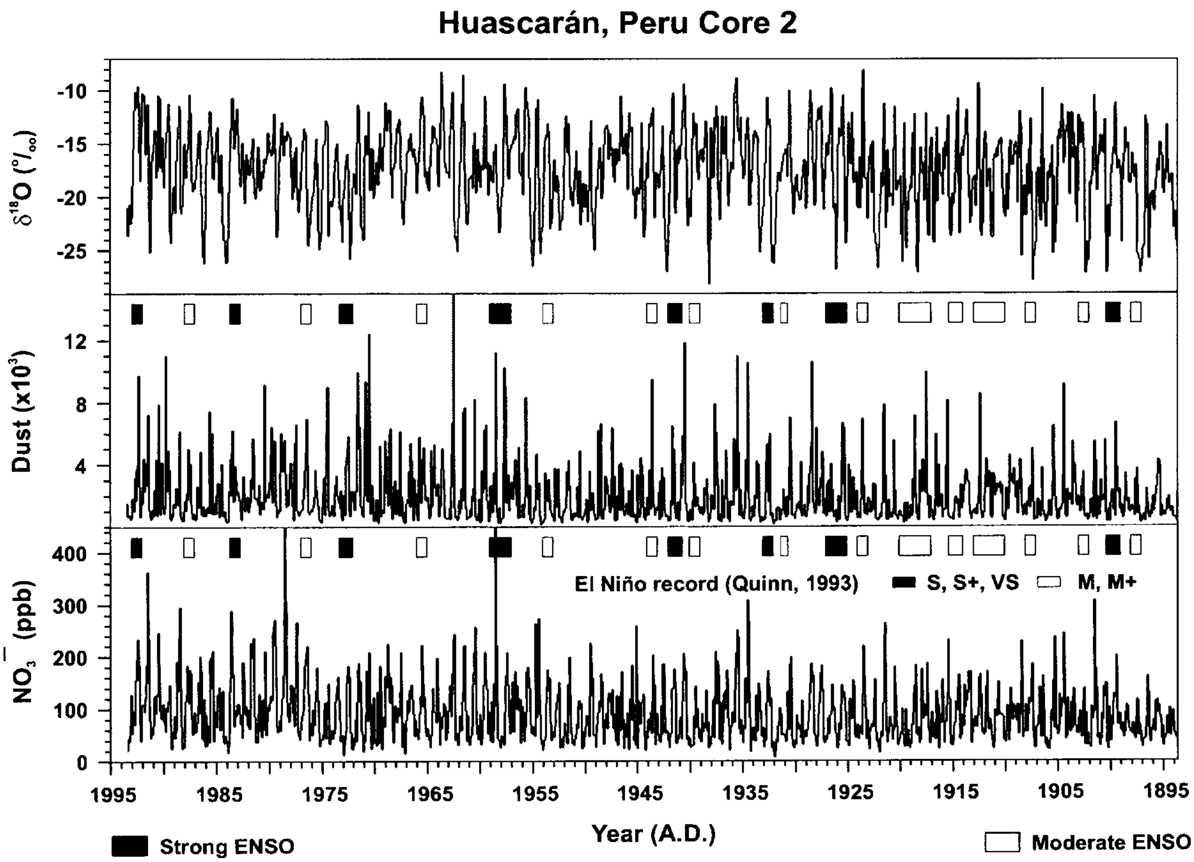
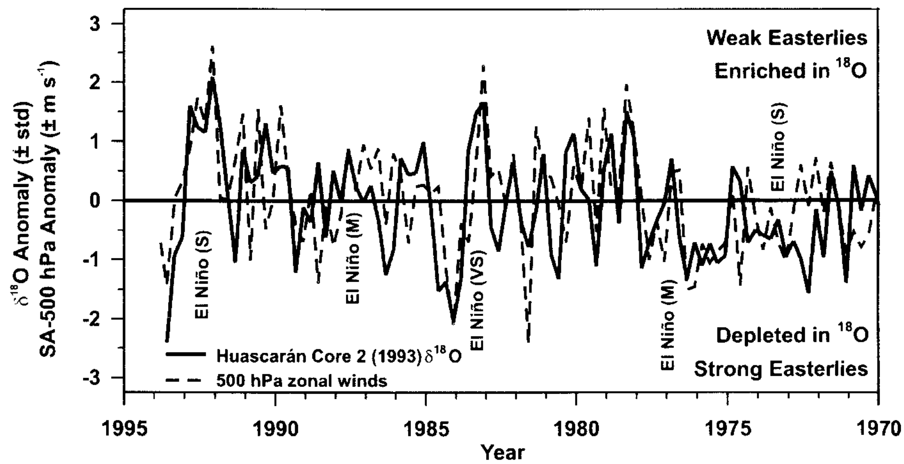
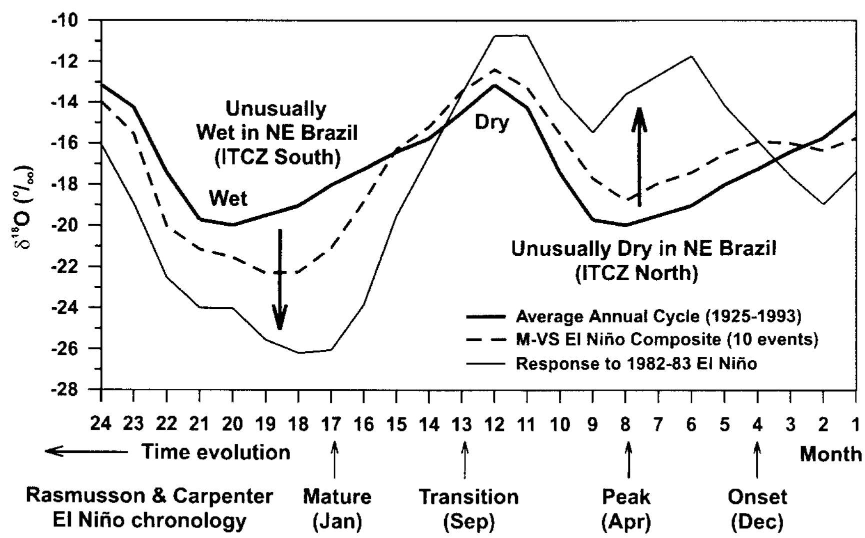


Fig. 12. Seasonal variations in $\delta^{18}O$, NO_3^-, and insoluble dust measured in Huascarán Core 2 for the last 100 yr. Also shown are the El Niño events identified by Quinn (1993). Note that El Niño strength is indicated by solid bars (very strong, strong plus and strong) and open bars (moderate and moderate plus events). Dust concentrations are per ml. of melted ice for particles with diameters > 2.0 µm. The $\delta^{18}O$ in the Huascarán cores, like those from Dasuopu above, exhibit a 15 + ‰ seasonal range and little attenuation of signal with depth.



Comparison of oxygen isotope anomalies (standardized departures from long-term monthly means) from Huascarán Core 2 (1993) and a composite index of zonal wind departures at the 500 hPa level derived from radiosonde measurements over nine stations in Brazil and Peru (averaged quarterly from 1970 to 1994)



Response to El Niño of $\delta^{18}O$ in the Huascarán Core 2 (1993) for the two-year period shown. A composite representing the last 10 moderate to very strong El Niño events is compared with the 1982-83 event and the normal variation in $\delta^{18}O$ due to the wet-dry seasonality over the Amazon.

Fig. 13. (a) Comparison of $\delta^{18}O$ anomalies (standardized departures from long-term monthly means) from Huascarán Core 2 and a composite index of zonal wind departures at the 500 hPa level derived from radiosonde measurements over nine stations in Brazil and Peru (averaged quarterly from 1970 to 1994). (b) Response of $\delta^{18}O$ to El Niño in Huascarán Core 2 for the 2-yr period shown. A composite representing the last 10 moderate to very strong El Niño events is compared with the 1982–83 event and the normal variation in $\delta^{18}O$ due to the wet–dry seasonality over the Amazon.

annual maximum corresponds to the mid-dry season, which is assumed to occur around the 1st of August. Because of rapid thinning in the Huascarán cores below 120 m, the time span of annual resolution was limited to 270 yr. However, the high accumulation and strong signal preservation also allowed for subannual resolution of the $\delta^{18}O$, insoluble dust and nitrate records for a period of 100 yr (1884–1993) as illustrated in Fig. 12. Subannual resolution of seasonal cycle can be justified since, the annual oxygen isotopic signal preserved in the ice core is remarkably evenly proportioned between the enriched (dry season) and depleted (wet season) isotopic values, despite the seasonal nature of precipitation at lower elevation sites in the tropics. The reasons for this are two-fold: (1) even in the dry season it will often snow on the mountain tops and (2) mass exchange by diffusion via

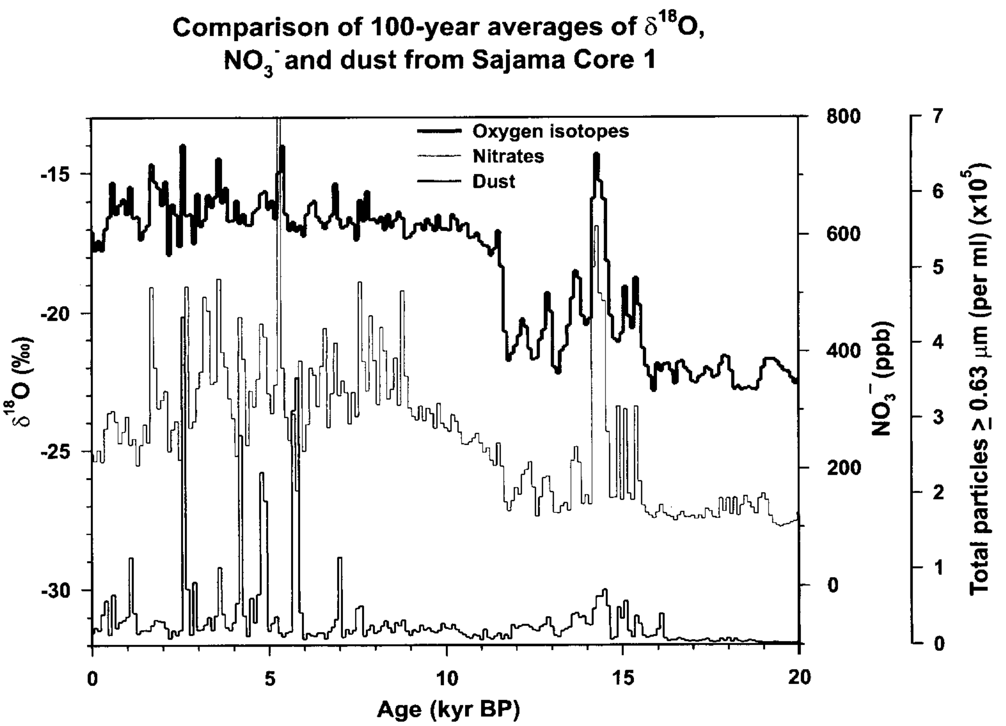


Fig. 14. The 100-yr averages in Sajama Core 1 of $\delta^{18}O$, insoluble dust, Cl^-, NO_3^-, and SO_4^{2-} concentrations are shown for the last 25,000 yr. Dating is based on a combination of an ice flow model, matching of $\delta^{18}O_{atm}$ and $\delta^{18}O_{ice}$ with GISP 2, and ^{14}C dating (Thompson *et al.*, 1998).

the vapor phase in porous snow tends to obliterate the higher frequencies $\delta^{18}O$ variations (see Thompson et al., 1999, in press). The accuracy of the time scale is of paramount importance in the development of relationships between ice core parameters and records of tropical climate conditions, particularly in the study of short-term climatic phenomenon like the El Niño-Southern Oscillations (ENSO). Fig. 13a illustrates the comparison of $\delta^{18}O$ anomalies (standardized departures from long-term monthly means) from Huascarán Core 2 and a composite index of zonal wind departures at the 500 hPa level derived from radiosonde measurements over nine stations in Brazil and Peru averaged quarterly from 1970 to 1994 (Henderson et al., 1999; Thompson et al., 1999). There is evidence that the spatial distribution of temperature anomalies in the western tropical Atlantic influences the 500 hPa circulation and hence affects isotopic fractionation. By conducting an event-based analysis involving the superposition of individual Warm (El Niño) and Cold epochs, Henderson et al. (1999) depicted the typical reaction of the Atlantic-driven tropical engine over Amazonia by identifying a characteristic 10 to 14 month half-period $\delta^{18}O$ wave in the composites (Fig. 13b). During an El Niño, the onset of the disturbance in the Atlantic occurs precisely at the peak positive anomaly in Pacific sea surface temperatures (SST), identifiable by the development of strongly enriched ^{18}O (significant at the 5% level) soon afterwards, and then a full reversal to strongly ^{18}O-depleted snowfall 10 to 14 months afterwards. A series of studies using EOF analyses of SST anomalies in the tropical Atlantic clearly show an analogue to the ENSO variability in the Pacific (see Thompson et al., 1999 for discussion). The characteristics of the Cold event composites are very similar but opposite, resulting in a strong negative correlation between Warm and Cold event composites in the year following peak anomaly development.

In 1997, two ice cores were recovered to bedrock from the summit of Sajama, Bolivia (Fig. 10) which provide the first ^{14}C dated tropical ice core records and confirm the presence of ice deposited during the LGS. The ^{18}O record indicates a 5.4‰ decrease between the Early Holocene and Last Glacial Maximum (LGM). During the transition from the LGM to the Holocene, the $\delta^{18}O$ record exhibits a return to near glacial conditions (Fig. 14), similar in magnitude to the Younger Dryas cooling recorded in the Greenland ice cores (Dansgaard et al. 1993; Greenland Ice core Project Members, 1993) but with an earlier onset starting at 14 kyr BP and lasting longer about 2500 yr while the termination of the event is within the accuracy of the time-scales appears at 11.5 kyr BP synchronous (Thompson et al., 1998). The onset and termination of the Sajama cold event were abrupt, occurring in less than a few centuries and suggesting atmospheric processes as the probable drivers. The time control provided by ^{14}C dates and $\delta^{18}O$ of atmospheric O_2 reveals significant accumulation increases, concurrent with high paleolake stands, between 9.5 and 14 kyr

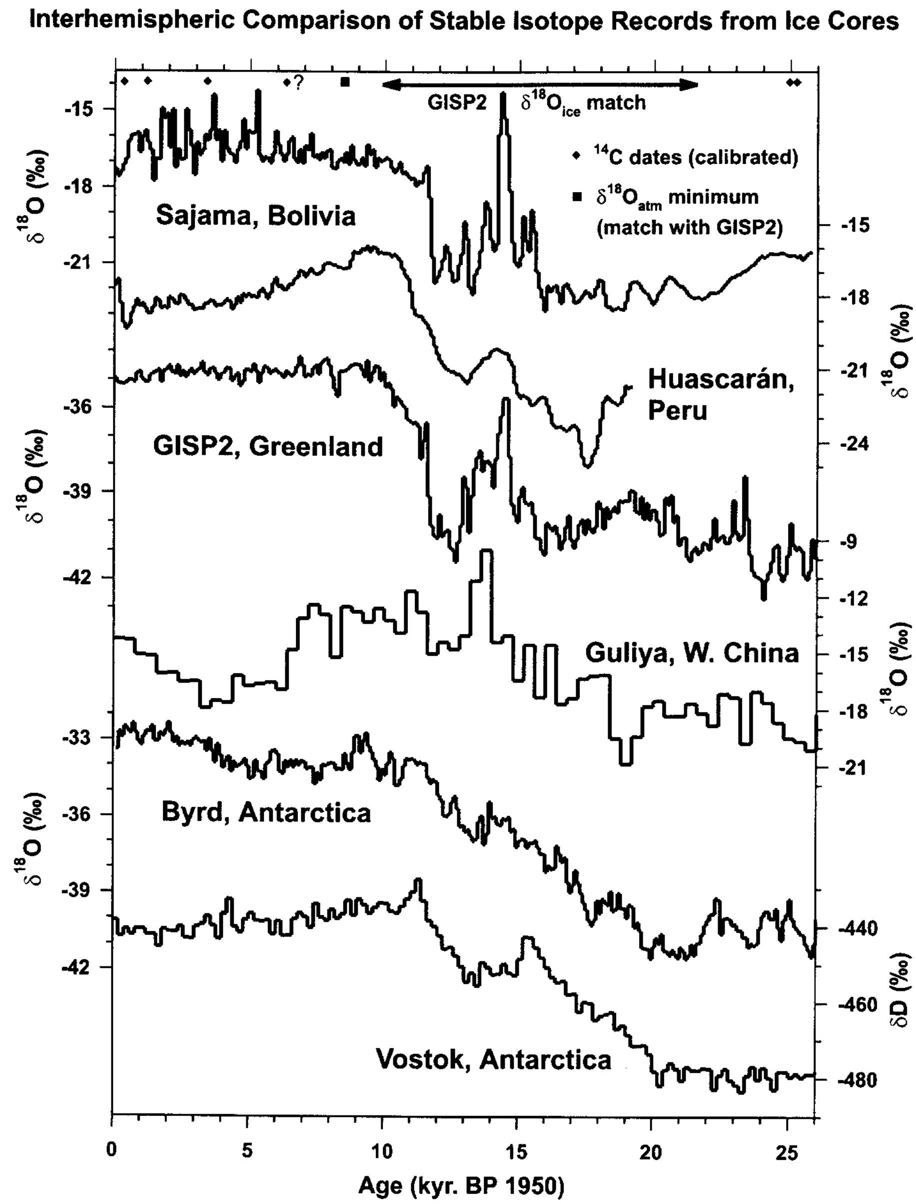


Fig. 15. This interhemispheric comparison of stable isotope records includes two tropical sites (Sajama and Huascarán), two Northern Hemisphere sites (Guliya and GISP 2) and two Southern Hemisphere sites (Byrd Station and Vostok). This shows the global extent of the LGS and the climatic reversal (cooling) during deglaciation (Thompson et al., 1998).

BP, 15.5 and 19 kyr BP and from 22 kyr BP to the end of the record. Fig. 14 illustrates that unlike polar cores, LGS ice contains eight times less dust than the Holocene, reflecting wetter LGS conditions on the Altiplano, more extensive snow cover, and decreased local volcanic activity. Meanwhile, the decrease in NO_3^- during the LGM, as in Huascarán (Thompson et al., 1995), is suggestive of drying of the Amazon source areas during the this period (Thompson et al., 1998).

The highly constrained time scale for the Sajama cores allows comparison of their $\delta^{18}O$ profiles with other tropical, subtropical and polar records (Fig 15). This global array of cores shows large scale similarities as well as important regional differences. The $\delta^{18}O$ shift from LGM to Early Holocene is seen in the 5.4‰ increase at Sajama (Thompson et al., 1998), 6.3‰ at Huascarán (Thompson et al., 1995), 5.4–5.1‰ at central Greenland (Grootes et al., 1993), 6.6‰ at Byrd Station, Antarctica (Johnsen et al., 1972) and 5.4‰ at Vostok, Antarctica (Jouzel et al., 1987). All these records show similar isotopic depletion, reflecting significant global cooling in the LGM in the water vapor source regions. These data contribute to a growing body of evidence that the LGM cooling was global coming from such diverse archives as corals (Guilderson et al., 1994; Beck et al., 1997; noble gases from groundwater (Stute et al., 1995); marine

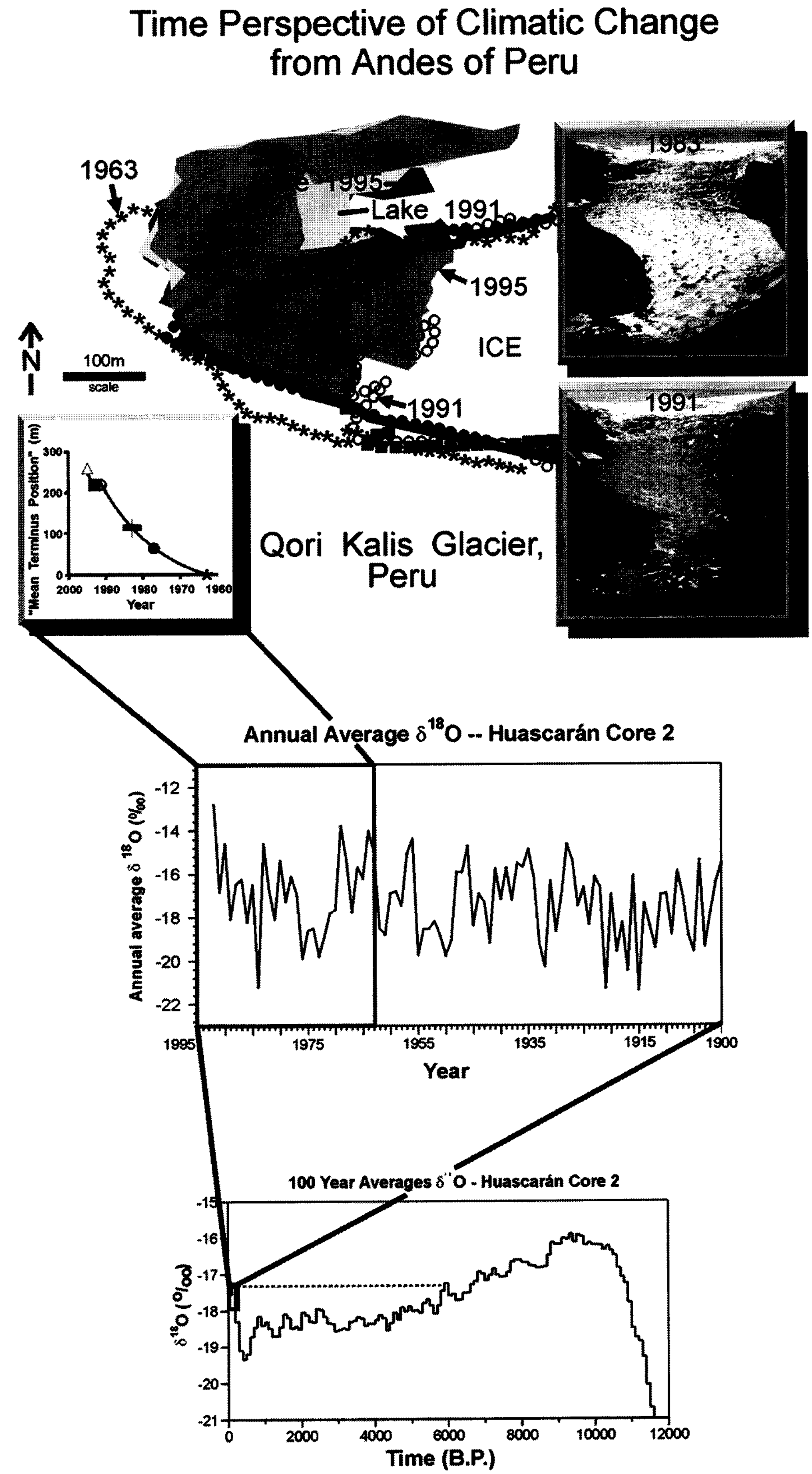


Fig. 16. Climate change in the Peruvian Andes. Upper part, a map of the changes in the extent of the tropical glacier Qori Kalis from 1963 to 1995, with photographs of the change over 8 years. The left-hand graph relates the shrinkage of Qori Kalis to the rising temperatures indicated by the ice-core data below it. Lower part, oxygen-isotope values from the Huascarán ice core. Bottom panel, century averages: top panel, annual averages since 1900.

sediment pore fluids (Schrag et al., 1996), snowline depression (Broecker and Denton, 1990; Herd and Naeser, 1974; Klein et al., 1995; Osmaston, 1965; Porter, 1979; Rodbell, 1992), and pollen studies (Colinvaux et al., 1996).

4. Tropical evidence for recent warming

Evidence is accumulating for a strong, recent warming in the tropics, which is causing rapid retreat and even disappearance of ice caps and glaciers at high elevations. These ice masses are particularly sensitive to small changes in ambient temperatures, since they already exist very close to the melting point. The warming and retreat of the Quelccaya ice cap in Peru has been well documented. Since 1976 Quelccaya has been visited repeatedly for extensive monitoring and sampling. In addition to the deep drilling in 1983, shallow cores were taken from the same area on the ice cap in 1976, 1991 and 1995. Comparison of the $\delta^{18}O$ records from these four years reveals that the seasonally resolved paleoclimatic record, formerly preserved as $\delta^{18}O$ variations, is no longer being retained within the currently accumulating snowfall (Thompson et al., 1993). The percolation of meltwater throughout the accumulating snowpack is evidently vertically homogenizing the $\delta^{18}O$.

The retreat of the margins of Quelccaya has also been investigated. The extent and volume of the largest outlet glacier, Qori Kalis, was measured six times between 1963 and 1995. These observations documented a drastic retreat that has accelerated during this 32-yr period. Brecher and Thompson (1993) reported that the rate of retreat from 1983 to 1991 was three times that from 1963 to 1983, and was five times faster in the most recent period (1993–1995). Associated with this increasing rate of retreat was a seven-fold increase in the rate of volume loss, as determined by comparing the 1963–1978 volume-loss rate to that of 1993–1995. The latest observations made in 1995 confirmed the continuation of Qori Kalis' accelerating melting (see Fig. 16, upper panel), as well as further retreat of the other margins of the Quel-

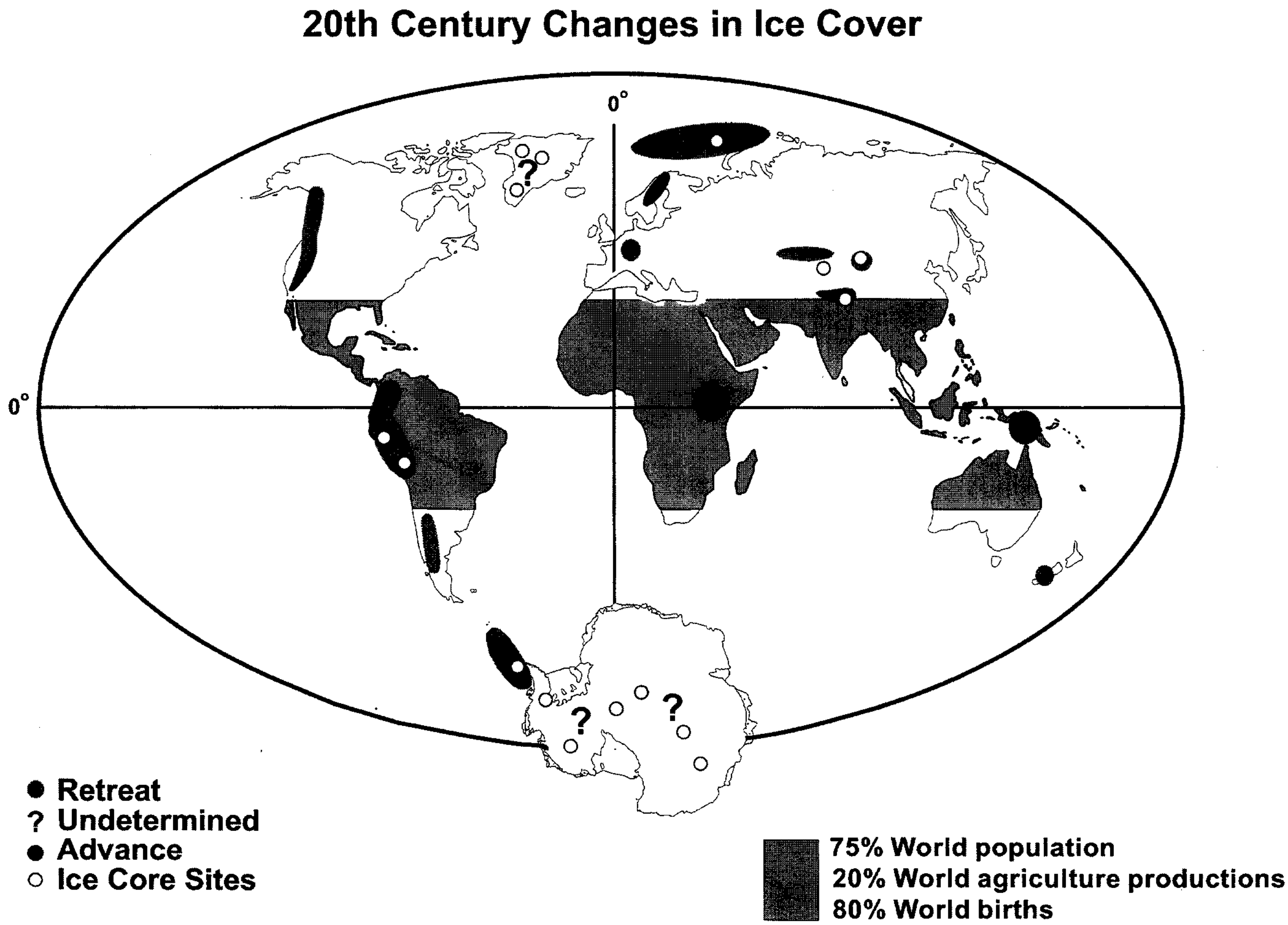


Fig. 17. Global view of the retreat of glaciers. Glaciers are a non political integrator of the global conditions of warming in the 20th century.

ccaya ice cap, and the development of three adjacent lakes which first appeared between 1983 and 1991.

The recent warming has also been observed in the higher elevation col of Huascarán, although here it has not been as drastic as on Quelccaya. The $\delta^{18}O$ data from the cores retrieved from Huascarán indicate that the nineteenth and twentieth centuries were the warmest in the last 6000 yr (Fig. 16, lower panels). The $\delta^{18}O$ profiles, plus meteorological observations made in the region reveal an accelerated rate of warming since 1970 (Davis et al., 1995), concurrent with the rapid retreat of ice masses throughout the Cordillera Blanca and of the Qori Kalis glacier.

Additional evidence from ice masses in Africa exists for recent warming in the tropics. Hastenrath and Kruss (1992) reported that the total ice cover on Mount Kenya has decreased by 40% between 1963 and 1987, while the Speke glacier in the Ruwenzori Range of Uganda has retreated substantially since it was first observed in 1958 (Kaser and Noggler, 1991). The shrinking of these ice masses in the high mountains of Africa and South America is consistent with similar observations throughout most of the world (Fig. 17). This general retreat of tropical glaciers is concurrent with an increase in water-vapor content of the tropical middle troposphere, which may have led to warming at this level (Flohn et al., 1990; Diaz and Graham, 1996).

5. Conclusions

The tropical and subtropical ice core records may potentially yield long annual to millennial-scale records of El Niño-Southern Oscillation events and monsoon variability and thus provide important insights into the magnitude and frequency of these large-scale events. These records also contain archives of decadal to millennial climatic and environmental variability, spanning large events from the so-called "Little Ice Age" to the Late Glacial Stage. The data presented above make it clear that some, if not all, of these unique archives are in imminent danger of being lost forever if the current warming persists, as is dramatically illustrated by the Quelccaya example. The loss of these natural glacier dams means less water in the dry seasons for agriculture and hydropower production, which severely impacts the lives of the people of these regions. It is ironic that the current warming which we seek to understand is acting to destroy the tropical glacier archives which can provide a long-term perspective of temperature changes and the clues to understanding the natural tropical climate variability on top of which the recent warming signal is imposed. The importance of understanding the tropical climate variability is made perfectly clear when we consider that 50% of the surface of the Earth lies between 30°N and 30°S, and more than 75% of the world's 6 billion people are directly impacted by variations in tropical climate.

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References

Bard, C., Arnold, M., Duprat, J., Moyes, J., Duplessy, J.-C., 1987. Retreat velocity of the North Atlantic polar front during the last deglaciation determined by 14C accelerator Spectrometry. Nature 328, 791–794.

Barnett, T., Dümenil, L., Schlese, U., Roeckner, E., Latif, M., 1989. The effect of Eurasian snow cover on regional and global climate variations. Journal of the Atmospherpic Sciences 46, 661–685.

Beck, J.W., Récy, J., Taylor, F., Edwards, R.L., Cabioch, G., 1997. Abrupt changes in early Holocene tropical sea surface temperature derived from coral records. Nature 385, 705–707.

Bradley, R.S., 1996. Are there optimum sites for global temperature reconstruction?. NATO ASI Ser.I 41, 603–624.

Brecher, H.H., Thompson, L.G., 1993. Measurement of the retreat of Qori Kalis in the tropical Andes of Peru by terrestrial photogrammetry. Photogrammetric Engineering Remote Sensing 59, 1017–1022.

Broecker, W.S., Denton, G.H., 1990. Implications of global snowline lowering during glacial time to glacial theory. Quaternary Science Reviews 9, 305–341.

Colinvaux, P.A., De Oliveira, P.E., Moreno, J.E., Miller, M.C., Bush, M.B., 1996. A long pollen record from lowland Amazonia; forest and cooling in glacial times. Science 274, 85–88.

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Gundestrup, N., 1973. Stable isotope glaciology. Meddeletser on Groenland 197, 1–53.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general

instability of past climate from a 250-kyr ice-core record. Nature 364, 218–220.
Davis, M.E., Thompson, L.G., Mosley-Thompson, E., Lin, P.N., Mikhalenko, V.N., Dai, J., 1995. Recent ice-core climate records from the Cordillera Blanca, Peru. Annals of Glaciology 21, 225–230.
Diaz, H.F., Graham, N.E., 1996. Recent changes in tropical freezing heights and the role of sea surface temperature. Nature 383, 152–155.
Fisher, D.A., Reeh, N., Clausen, H.B., 1985. Stratigraphic noise in time series derived form ice cores. Annals of Glaciology 7, 76–83.
Flohn, H., Kapala, A., Knoche, H.R., Machel, H., 1990. Recent changes of the tropical water energy budget and of mid-latitude circulations. Climate Dynamics 4, 237–252.
Greenland Ice-Core Project Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. Nature 364, 203–207.
Grootes, P.M. 1995. Ice cores as Archives of Decade-to-Century-Scale Climate Variability. Natural Climate Variability on Decade-to-Century Time Scales. National Research Council, pp. 544–554.
Grootes, P.M., Stuvier, M., Thompson, L.G., Mosley-Thompson, E., 1989. Oxygen isotope changes in tropical ice, Quelccaya, Peru. Journal of Geophysical Research 94 (D1), 1187–1194.
Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S., Jouzel, J., 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366, 552–554.
Guilderson, T.P., Fairbanks, R.G., Rubenstein, J.L., 1994. Tropical temperature variations since 20,000 years ago; modulating inter-hemispheric climate change. Science 263, 663–665.
Hardy, D.R., Vuille, M., Braun, C., Keimig, F., Bradley, R.S., 1998. Annual and daily meteorological cycles at high altitude on a tropical mountain. Bulletin of the American Meteorological Society 79, 1899–1913.
Hastenrath, S., Kruss, P.D., 1992. The dramatic retreat of Mount Kenya's glaciers between 1963 and 1987: Greenhouse forcing. Annals of Glaciology 16, 127–133.
Herd, D.G., Naeser, C.W., 1974. Mountain snowline lowering in the tropical Andes. Geology 2, 603–604.
Henderson, K.A., Thompson, L.G., Lin., P.-N., 1999. The recording of El Niño in ice core $\delta^{18}O$ records from Nevado Huascarán, Peru. Journal of Geophysical Research, in press.
Johnsen, S.J., Dansgaard, W., Clausen, H.B., Langway Jr., C.C., 1972. Oxygen isotope profiles through the Antarctic and Greenland ice sheets. Nature 235, 429–433.
Jouzel, J., Lorius, C., Petit, J.R., Genthon, C., Barkov, N.I., Kotlyakov, V.M., Petrov, V.M., 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). Nature 329, 403–408.
Kaser, G., Noggler, B., 1991. Observations on Speke Glacier, Ruwenzori Range, Uganda. Journal of Glaciology 37, 315–318.
Kerr, R.A., 1998. Sea-floor dust shows drought felled Akkadian Empire. Science 279, 325–326.
Klein, A.G., Isacks, B.L., Bloom, A.L., 1995. Modern and Last Glacial Maximum Snowline in Peru and Bolivia: implications for regional climatic change. Bulletin de l'Institut Français d'Études Andines 24, 607–617.
Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R., Laarif, F., 1998. Climate and biome simulations for the past 21,000 years. Quaternary Science Reviews 17, 473–506.
Li, Y.-F., 1997. Global Population Distribution (1990), Terrestrial Area, and Country Name Information on a One-by-One Degree Grid-Cell Basis. Compiler: A.L. Brenkert, CDIAC, DB-1016 (1996)
Liu, K.-b., Yao, Z., Thompson, L.G., 1998. A pollen record of Holocene climatic changes form the Dunde ice cap, Qinghai-Tibetan Plateau. Geology 26, 135–138.
Mosley-Thompson, E., Dai, J., Thompson, L.G., Grootes, P.M., Arbogast, J.K., Paskievitch, J.F., 1991. Glaciological studies at Siple Station (Antarctica): potential ice-core paleoclimatic record. Journal of Glaciology 37, 11–22.
Osmaston, H.A., 1965. Snowline lowering on the mountains of tropical Africa. Ph.D. Thesis, Oxford University, Worcester College.
Paterson, W.S.B., 1994. The Physics of Glaciers, 3rd Edition. Pergamon, Elsevier Science Ltd., Oxford, England.
Porter, S.C., 1979. Glacial snowline lowering in Hawaii. Geological Society of America Bulletin 90, 980–1093.
Quinn, W.H., 1993. The large-scale ENSO event, the El Niño and other important regional patterns. Bulletin de l'Institut Français d'Études Andines 22, 13–34.
Rodbell, D.T., 1992. Snowline lowering in the Peruvian Andes. Boreas 21, 43–52.
Rozanski, K., Johnsen, S.J., Schotterer, U., Thompson, L.G., 1997. Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives. Hydrological Sciences-Journal des Sciences Hyrologiques 42, 725–745.
Schrag, D.P., Hampt, G., Murray, D.W., 1996. Pore fluid constraints on the temperature and oxygen isotopic composition of the Glacial ocean. Science 272, 1930–1932.
Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., Duplessy, J.C., 1993. Century-scale events in monsoonal climate over the past 24,000 years. Nature 364, 322–324.
Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J.F., Schlosser, P., Broecker, W.S., Bonani, G., 1995. Cooling of tropical Brazil (5°C) during the last glacial maximum. Science 269, 379–383.
Thompson, L.G., Dansgaard, W., 1975. Oxygen isotope and microparticle investigation of snow samples from the Quelccaya Ice Cap, Peru. Peru. Antarctic Journal of the U.S. 10, 24–26.
Thompson, L.G., Davis, M.E., Mosley-Thompson, E., Liu, K.-b., 1988. Pre-Incan agricultural activity recorded in dust layers in two tropical ice cores. Nature 336, 763–765.
Thompson, L.G., Mosley-Thompson, E., Bolzan, J.F., Koci, B.R., 1985. A 1500 year record of tropical precipitation recorded in ice cores from the Quelccaya Ice Cap, Peru. Science 229, 971–973.
Thompson, L.G., Mosley-Thompson, E., Dansgaard, W., Grootes, P.M., 1986. The "Little Ice Age" as recorded in the stratigraphy of the tropical Quelccaya ice cap. Science 234, 361–364.
Thompson, L.G., Mosley-Thompson, E., Grootes, P.M., Pourchet, M., Hastenrath, S., 1984. Tropical Glaciers: potential for ice core Paleoclimatic reconstructions. Journal of Geophysical Research 89 (D3), 4638–4646.
Thompson, L.G., Mosely-Thompson, E., Davis, M.E., Bolzan, J., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L., Xie, Z., 1989. Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. Science 246, 474–477.
Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.-N., Yao, T., Dyurgerov, M., Dai, J., 1993. "Recent warming": ice core evidence from tropical ice cores with emphasis upon Central Asia. Global and Planetary Change 7, 145–156.
Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.-N., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K.-b., 1995. Late Glacial Stage and Holocene Tropical Ice Core Records from Huascaran, Peru. Science 269, 47–50.
Thompson, L.G., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., Bolzan, J.F., 1997. Tropical climate instability: the Last Glacial Cycle from a Qinghai-Tibetan Ice Core. Science 276, 1821–1827.
Thompson, L.G., Davis, M.E., Mosley-Thompson, E., Sowers, T.A., Henderson, K.A., Zagorodnov, V.S., Lin, P.-N., Mikhalenko, V.N., Campen, R.K., Bolzan, J.F., Cole-Dai, J.A., 1998. 25,000 year tropical climate history form Bolivian Ice Cores. Science 282, 1858–1864.

Thompson, L.G., Henderson, K.A., Mosley-Thompson, E., Lin, P.-N., 1999. The tropical ice core record of ENSO. In: Diaz, H., Markgraf, V., (Eds.), El Niño and the Southern Oscillation Multiscale Variability, Global and Regional Impacts, in press.

Vuille, M., Hardy, D.R., Braun, C., Keimig, F., Bradley, R.S., 1998. Atmospheric circulation anomalies associated with 1996/1997 summer precipitation events on Sajama Ice Cap, Bolivia. Journal of Geophysical Research 103 (D10), 11191–11204.

Yao, T., Thompson, L.G., Mosley-Thompson, E., Zhihong, Y., Xingping, Z., Lin, P.-N., 1996. Climatological significance of $\delta^{18}O$ in north Tibetan ice cores. Journal of Geophysical Research 101 (D23), 29 531–29 537.